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Analysis on combustion and emission of hydrogen-LNG blends in a medium-speed LNG dual-fuel engine

Fuels - Alternative & New Fuels

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ABSTRACT

To meet greenhouse gas (GHG) emission regulations set by the IMO and the EU, hydrogen is emerging as a pivotal future fuel offering high economic viability and broad applicability. In the maritime sector, hydrogen's use as fuel is expected to be divided into two primary applications: fuel cells and internal combustion engines. Among these, internal combustion engines show greater potential as propulsion and power generation sources for large vessels due to their high controllability, power density, and relatively low cost. However, hydrogen has a low ignition energy and rapid flame speed, requiring precise control logic to prevent knocking or pre-ignition when applied in internal combustion engines. This study focuses on applying hydrogen to a HiMSEN dual-fuel engine, a four-stroke mid-speed engine for marine and stationary applications. The engine was tested by blending hydrogen with natural gas in dual-fuel operation mode, followed by conducting hydrogen-diesel dual-fuel combustion tests without natural gas. Low-pressure hydrogen was supplied to the intake port in both scenarios. During the tests, the compression ratio, turbocharger specifications, and pilot injection timing and quantity were evaluated to maximize the hydrogen blending ratio and engine efficiency while preventing knocking and pre-ignition. Additionally, compliance with IMO NOx regulations was confirmed, demonstrating effective reduction of GHG emissions through hydrogen blending in existing LNG dual-fuel engines.

1 INTRODUCTION

The growing urgency to mitigate greenhouse gas (GHG) emissions has prompted significant regulatory actions from international organizations such as the International Maritime Organization (IMO) and the European Union [1]. The maritime industry, responsible for approximately 3% of global energy demand, faces increasing pressure to adopt cleaner energy solutions [2]. As global transportation continues to expand, so too does the demand for more sustainable and efficient propulsion technologies in the shipping sector. In response, hydrogen has emerged as a promising alternative fuel due to its zero-carbon combustion characteristics, high energy density, and potential for economic feasibility [3]. Given its versatility, hydrogen is being explored for various applications, particularly in fuel cells and internal combustion engines. While fuel cells offer high efficiency and zero emissions, their application in large vessels remains limited due to high costs, infrastructure challenges, and power density constraints [4]. In contrast, internal combustion engines provide a more practical and cost-effective solution for large-scale maritime applications, leveraging existing engine designs while reducing carbon and pollutant emissions through hydrogen utilization.

Hydrogen as a fuel presents unique challenges in internal combustion engines, particularly in terms of its low ignition energy, rapid flame speed, high flame temperature, and high diffusivity [5]. These properties can lead to pre-ignition and knocking issues, requiring advanced combustion control strategies to ensure stable and efficient engine operation. Various methods, such as dual-fuel (DF) operation, have been investigated to address these challenges while optimizing engine performance [6]. One promising approach involves blending hydrogen with other fuels such as natural gas (NG) or diesel to achieve a balance between efficiency, emissions reduction, and combustion stability. The combustion characteristics of hydrogen in DF engines extremely vary depending on the ratio of hydrogen in the fuel mixture, the engine operating conditions, and the engine and auxiliary equipment configuration. Additionally, hydrogen's high flame speed can contribute to higher thermal efficiency if controlled properly, but also increases the risk of abnormal combustion phenomena, necessitating precise control mechanisms.

This study focuses on the application of hydrogen in a HiMSEN DF engine, a four-stroke mid-speed engine used in marine propulsion and stationary power generation. The research explores two primary dual-fuel combustion strategies: hydrogen-NG blending and hydrogen-diesel operation. In both cases, hydrogen at a relatively low pressure of less than 15 bar is introduced into the intake port, and engine parameters, including compression ratio, engine coolant temperatures, turbocharger specifications, and diesel injection timing and quantity, are analyzed to determine their effects on allowable maximum hydrogen ratio, engine efficiency, and emissions characteristics. The potential for reducing carbon dioxide (CO_2) and nitrogen oxides (NOx) is also evaluated in comparison with conventional diesel or diesel-NG DF engines. Moreover, different strategies for mitigating knocking and pre-ignition are assessed to ensure safe and reliable hydrogen combustion in maritime applications.

By investigating the feasibility and effectiveness of hydrogen combustion in dual-fuel internal combustion engines, this research aims to provide valuable insights into practical pathways for reducing maritime emissions. The findings will contribute to the ongoing development of hydrogen-powered marine propulsion systems and offer guidance on optimizing engine configurations for future regulatory compliance and operational efficiency. As the maritime industry transitions toward a greener future, the integration of hydrogen in existing engine technologies represents a significant step forward in achieving long-term sustainability goals while maintaining the economic viability of shipping operations.

2 METHODOLOGY

2.1 Hydrogen Supply System

To ensure safe and reliable engine experiments, a stable hydrogen supply system is essential. An integrated skid system that utilizes high-pressure hydrogen tank trailer as a hydrogen storage unit was established. The system supplies hydrogen through controlled pressure reduction and flow regulation, and mixes the hydrogen with externally supplied natural gas at precise ratios for hydrogen-NG blend engine operations. The integrated skid system is shown in Figure 1.

Figure 1. Hydrogen supply skid system.

The regulator section of the skid consists of a primary pressure reduction valve, which lowers the hydrogen pressure of up to 200 bar from the trailer to below 50 bar, and a secondary regulating valve, which controls the supply pressure below 10 bar, regardless of the hydrogen flow rate required by the engine. Additionally, the system includes several on/off valves, safety valves, venting lines, and pressure and temperature sensors. The mixer section of the skid introduces an accurate ratio of hydrogen-NG blend gas during the experiments. A flow control valve that regulates the hydrogen flow rate in relation to the total gas flow was used. The mixer features a specially designed internal pipe structure to enhance the mixing performance. After the mixing, gas samples are collected by a probe and analyzed using gas chromatography to monitor the hydrogen-NG ratio and adjust the hydrogen flow control valve based on feedback control from the gas composition analysis.

2.2 Engine Setup

The HiMSEN H22CDF engine, a four-stroke mid-speed dual-fuel engine for marine and stationary applications, manufactured by HD Hyundai Heavy Industries, was used. The specifications of the engine are shown in Table 1.

Table 1. Engine specification.

Specification	Value
Bore (mm)	220
Stroke (mm)	330
Rated Speed (rpm)	900
Rated Power (kW/cyl.)	215
BMEP (bar)	22.9
Main Fuel Oil System	Mechanical Pump Line Nozzle
Pilot Fuel Oil System	Electronic Common Rail
Gaseous Fuel System	Gas Admission Valve

The engine configuration was basically identical to that of HiMSEN DF engines using diesel and natural gas. However, some components were modified to adapt to the physical and chemical properties of hydrogen. The control parameters of the gas regulator unit, which supplies gaseous fuel to the engine at a constant pressure, was adjusted to work with the hydrogen supply skid. The gas admission valve, which injects gaseous fuel into the intake port, was replaced with a unit compatible with hydrogen operation. Also, to ensure stable hydrogen combustion, optimization of engine parameters such as compression ratio, coolant temperature, charge air pressure and temperature, and turbocharger specifications was carried out. The control of hydrogen or hydrogen-NG blend gas supply, as well as the co-firing ratio with diesel, was managed using the fuel sharing function of the engine control unit. When the fuel sharing function becomes active, the controller automatically adjusts the amount of injected gaseous fuel into the intake port, based on open duration of the gas admission valve. The schematics of the engine combustion system are shown in Figure 2.

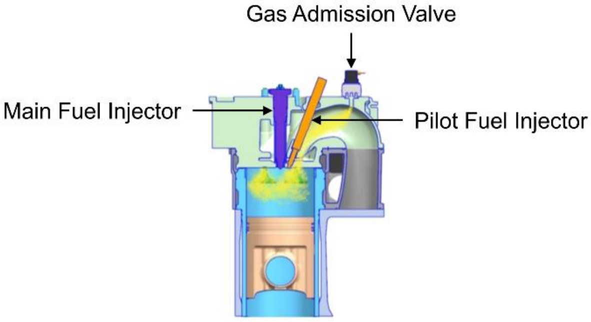

Figure 2. Schematics of the engine system.

3 EXPERIMENTAL RESULTS

3.1 Hydrogen-NG Blend

The hydrogen-NG blend gas was ignited by the diesel pilot fuel, which is a same combustion principle as the gas mode of the DF engine. To evaluate how much natural gas could be replaced with hydrogen in dual-fuel operation, hydrogen was gradually blended into the gas while the engine was running with natural gas.

Since hydrogen-NG combustion involves three different fuels, including diesel pilot fuel, its application in marine engines poses practical constraints. Therefore, this section aimed to observe the combustion characteristics affected by hydrogen blending and analyze engine performance and emission trends before increasing the hydrogen ratio without natural gas. The predefined hydrogen blending ratios applied in this experiment are shown in Figure 3.

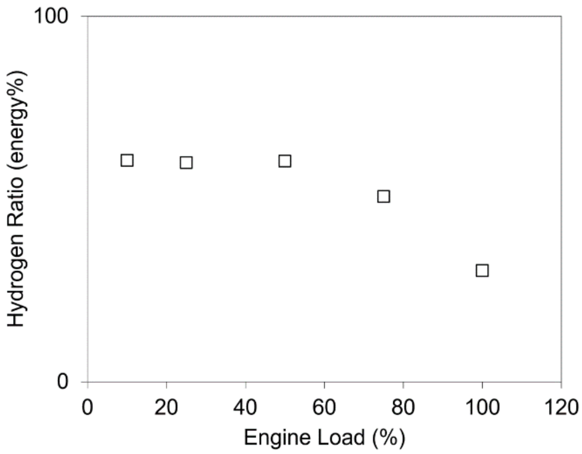

Figure 3. Hydrogen-NG blending ratio.

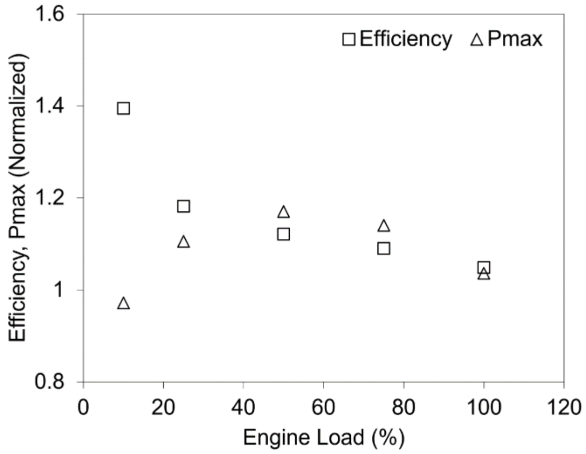

Figure 4. Engine efficiency and Pmax, compared to NG operation.

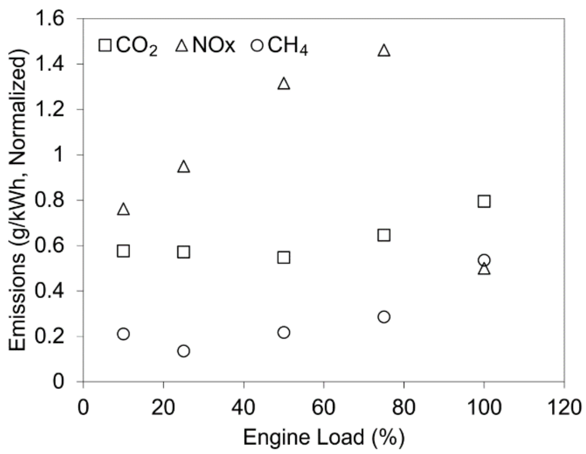

Figure 5. CO_2, NOx, and CH_4 emissions, compared to NG operation.

The results of comparing engine efficiency and the maximum combustion pressure (Pmax) while blending hydrogen to natural gas at the specified ratios are presented in Figure 4. Compared to natural gas-only operation, the engine efficiency improved with hydrogen blending, increasing by up to 40% at low load and approximately 5% at high load. Maximum combustion pressure showed a slight decrease under certain low-load conditions, but increased by as much as 15% across the entire engine operation range.

Figure 5 presents the changes in CO_2, NOx, and CH_4 emissions. For CO_2, emissions decreased in proportion to the amount of hydrogen, since a carbon-free fuel was blended to the hydrocarbon fuels. NOx emissions decreased under low-load conditions but increased as the load increased, surpassing the results of natural gas combustion at medium load, and finally decreased again at full load. While NOx emissions were expected to rise due to hydrogen's faster and hotter combustion compared to natural gas, this result may affected by different engine control and operational parameters such as intake pressure or pilot fuel injection. Therefore, further research is required to better understand the effects of hydrogen on NOx formation. Finally, CH_4 emissions, which mainly comes from methane slip, significantly decreased across the entire engine operating range, with a reduction rate exceeding the proportion of hydrogen addition. This is due to hydrogen's faster combustion, promoting the oxidation of natural gas, thereby reducing unburned methane.

3.2 Hydrogen-Diesel Fuel Sharing

As the next step, fuel sharing tests were conducted using only hydrogen and diesel, excluding natural gas. Unlike the hydrogen-NG blend operation, this experiments were conducted in diesel mode. As the engine operated on diesel with the main fuel injection, hydrogen was gradually increased to replace a portion of the diesel fuel. With minimal engine hardware modifications, the maximum hydrogen ratio obtained by the optimization of control parameters, such as charge air pressure and temperature, coolant temperature, and fuel injection timing, was determined.

As shown in Figure 6, the maximum available hydrogen ratio decreased at higher loads in terms of energy share. This limitation is primarily due to an excessive combustion pressure, excessive exhaust temperature, excessive engine cycle variations, and insufficient turbocharger waste gate control margin, resulted by fast combustion speed and high combustion temperature. Additionally, various abnormal combustion phenomena, such as backfire, pre-ignition, or misfire, were occasionally observed. At low loads, combustion control instability due to the reduced diesel injection quantity, and at high loads, excessive combustion pressure and abnormal combustion, were the primary limitations.

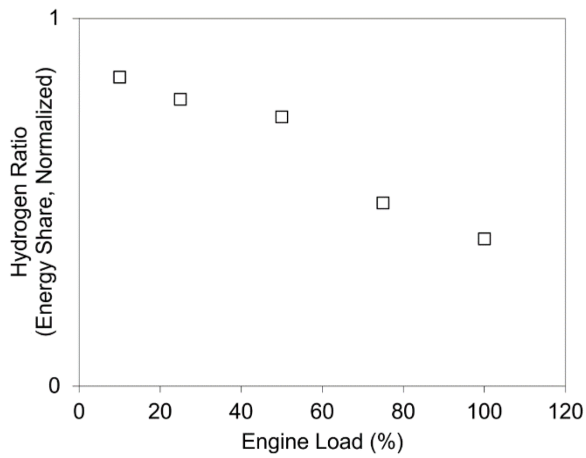

Figure 6. Maximum hydrogen ratio.

In Figure 7, Pmax comparison across various load and fuel conditions is shown. For each load condition, the maximum combustion pressure in diesel mode was set as a reference value, and the combustion pressures in NG gas mode and hydrogen-diesel fuel sharing mode were compared accordingly. In gas mode using natural gas, the Pmax was up to 20% lower than in diesel mode. However, during hydrogen-diesel fuel sharing, Pmax exceeded that of diesel combustion. At low loads, the maximum combustion pressure was approximately 10% lower, whereas at medium to high loads, it increased by about 2 – 4%.

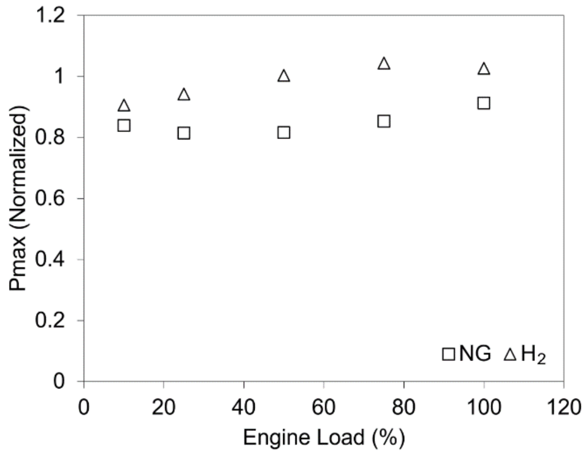

Figure 7. Comparison of Pmax for NG and diesel-hydrogen fuel sharing with diesel combustion.

Figure 8 and 9 show the comparison of engine efficiency and NOx emissions during hydrogen-diesel fuel sharing, with diesel mode as the baseline. Unlike hydrogen-NG blend combustion where hydrogen improved the engine efficiency, the efficiency decreased particularly at low loads, where it dropped by more than 30%, as shown in Figure 8. A possible reason for this efficiency loss is the significant difference in combustion characteristics between hydrogen and diesel. At the current air-fuel ratio range, the combustion speed of hydrogen is not drastically higher than that of natural gas, which allows hydrogen to enhance the oxidation process of natural gas in a blend. However, hydrogen burns much faster than diesel, and diesel has a considerably longer ignition delay. As a result, the two fuels do not combust at optimal timing relative to each other. This misalignment in combustion timing is suspected to be the primary reason for the efficiency reduction. Although not presented in this paper, an analysis of in-cylinder heat release rates indicated that hydrogen combustion occurred at a very early timing, before diesel combusts. In addition, these differences between two fuels were more dominant at low loads, where the quantity of diesel injected was relatively small.

In terms of NOx emissions, a general decreasing trend was observed compared to diesel mode. The reduction was particularly prominent at low loads, where NOx decreased by more than 65%. Diesel mode operation typically shows higher NOx than gas mode using natural gas, due to fast combustion near TDC, which leads to higher combustion temperatures, as well as leaner air-to-fuel ratio compared to gas mode, resulting in higher oxygen concentration. However, even considering this tendency, the NOx reduction in hydrogen-diesel fuel sharing is notable. A potential explanation for this reduction is that hydrogen, which replaces a portion of diesel fuel, ignites before diesel at non-optimal timing. This early combustion lowers the oxygen concentration inside the cylinder without significant temperature rise, thereby limiting NOx formation. Additionally, hydrogen radicals actively consume reaction intermediates such as OH, by hydrogen radicals in the oxidation reaction, which interferes the oxidation of nitrogen. This effect is previously suggested in other studies as the result of adding hydrogen to hydrocarbon fuels [5].

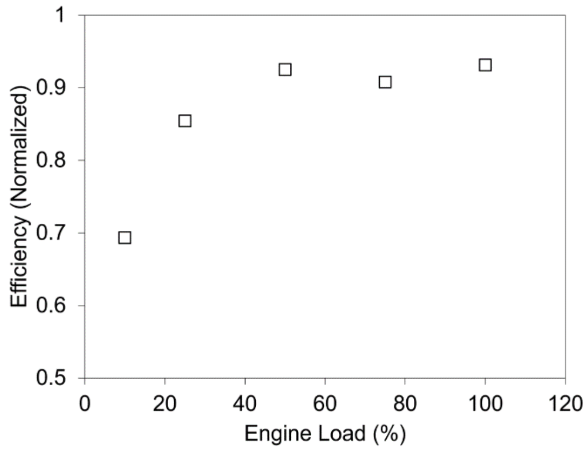

Figure 8. Engine efficiency, compared to diesel mode.

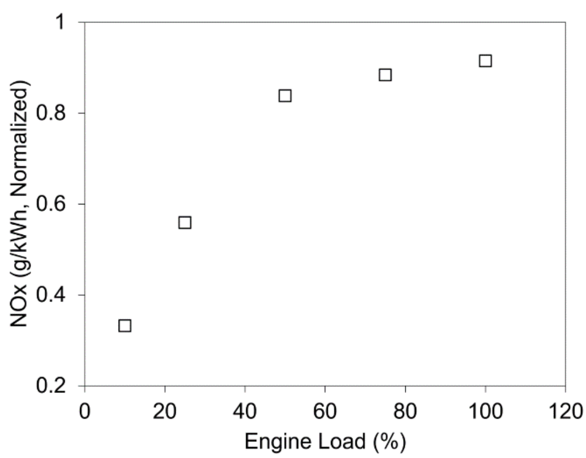

Figure 9. NOx emission, compared to diesel mode.

4 CONCLUSIONS

The impact of hydrogen blended combustion on engine performance, combustion, and emissions characteristics was analyzed for a multi-cylinder, four-stroke, mid-speed marine engine.

- An integrated skid system was established to supply hydrogen to the engine at stable pressure and flow rates, and to mix hydrogen with natural gas in precise proportions. Some engine components and control variables were modified for hydrogen operation.

- During gas mode operation using natural gas, hydrogen was mixed to implement hydrogen-NG blend fuel combustion. Increased Engine efficiency, increased combustion pressure, a slight increase in NOx emission under certain conditions, and a reduction in methane slip were observed with hydrogen blending.

- During diesel mode operation, hydrogen was injected into the intake port to implement hydrogen-diesel fuel sharing, and the maximum hydrogen ratio achievable with the current engine configuration was determined. Decreased engine efficiency and NOx emission reduction were observed with hydrogen-diesel combustion.

- This study serves as a foundational research for development of decarbonized vessels by replacing hydrocarbon fuels with hydrogen. Further research is required for fine-tuning combustion variables to optimize engine parameters.

5 DEFINITIONS, ACRONYMS, ABBREVIATIONS

CH_4: Methane

CO_2: Carbon Dioxide

DF: Dual Fuel

GHG: Greenhouse Gas

IMO: International Maritime Organization

NG: Natural Gas

NOx: Nitrogen Oxides

OH: Hydroxyl Radical

Pmax: Maximum Combustion Pressure

TDC: Top Dead Center

6 ACKNOWLEDGMENTS

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